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For: **MULTI-WAVELENGTH OPTICAL FIBER**

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## **MULTI-WAVELENGTH OPTICAL FIBER**

### **Cross-Reference to Related Applications**

[0001] This application is a continuation of International Application No. PCT/US02/20817, which has an international filing date of July 1, 2002, and is entitled "Multi-Wavelength Optical Fiber", and which in turn claims priority to United States Provisional Patent Application Serial No. 60/302,603, which was filed July 2, 2001 and is also entitled "Multi-Wavelength Optical Fiber". The foregoing applications are incorporated herein by reference.

### **Technical Field**

[0002] This invention relates to optical fibers (e.g., fiber lasers and fiber amplifiers), and systems containing such optical fibers.

### **Background**

[0003] Certain optical fibers can be used as fiber amplifiers or fiber lasers.

[0004] Fiber amplifiers are typically used to amplify an input signal. Often, the input signal and a pump signal are combined and passed through the fiber amplifier to amplify the signal at the input wavelength. The amplified signal at the input wavelength can then be isolated from the signal at undesired wavelengths.

[0005] Raman fiber lasers can be used, for example, as energy sources. In

general, Raman fiber lasers include a pump source coupled to a fiber, such as an optical fiber, having a gain medium with a Raman active material. Energy emitted from the pump source at a certain wavelength  $\lambda_p$ , commonly referred to as the pump energy, is coupled into the fiber. As the pump energy interacts with the Raman active material in the gain medium of the fiber, one or more Raman Stokes transitions can occur within the fiber, resulting in the formation of energy within the fiber at wavelengths corresponding to the Raman Stokes shifts that occur (e.g.,  $\lambda_{s1}$ ,  $\lambda_{s2}$ ,  $\lambda_{s3}$ ,  $\lambda_{s4}$ , etc.).

[0006] Generally, the Raman active material in the gain medium of a Raman fiber laser may have a broad Raman gain spectrum. Usually, conversion efficiency varies for different frequencies within the Raman gain spectrum and many Raman active materials exhibit a peak in their gain spectrum, corresponding to the frequency with highest conversion efficiency. Additionally, the gain spectrum for different Raman active materials may be substantially different, partially overlapping, or of different conversion efficiency.

[0007] Typically, a Raman fiber laser is designed so that the energy formed at one or more Raman Stokes shifts is substantially confined within the fiber. This can enhance the formation of energy within the fiber at one or more higher order Raman Stokes shifts. Often, the fiber is also designed so that at least a portion of the energy at wavelengths corresponding to predetermined, higher order Raman Stokes shifts (e.g.,  $\lambda_{sx}$  where x is equal to or greater than one) is allowed to exit the fiber.

### **Summary**

[0008] In general, the invention relates to optical fibers (e.g., fiber lasers and fiber amplifiers), and systems containing such optical fibers.

[0009] In one aspect, the invention features a fiber that includes an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum. The optical fiber is configured to receive energy at a wavelength  $\lambda_p$ . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each pair of

reflectors forms a resonance cavity with a resonance frequency. Each resonance cavity has an index, and the index of each resonance cavity is different than the index of the other resonance cavities. For a resonance cavity having an index with a value M (M is an integer having a value of at least one), the resonance cavity has a resonance frequency  $(c/\lambda_{sm})$ , where  $\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$ , where  $(c/\lambda_{rm})$  is a frequency within the Raman gain spectrum of the Raman active material contained in the gain medium, and c is the speed of light. For a resonance cavity having an index with a value N, the resonance cavity has a resonance frequency  $(c/\lambda_{sn})$ . The resonance cavity having the index value N overlaps only with a resonance cavity having a resonance frequency  $(c/\lambda_{s(n-1)})$  and with a resonance cavity having a resonance frequency  $(c/\lambda_{s(n+1)})$  (N is an integer having a value of at least two). In the case where N corresponds to the highest index number (i.e., the cavity with the lowest resonance frequency), the cavity overlaps only with a resonance cavity having a resonance frequency  $(c/\lambda_{s(n-1)})$ .

**[0010]** For example,  $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$ , where  $\lambda_{r1}^{-1}$  is a frequency in the Raman gain spectrum of the active material. As another example,  $\lambda_{s2}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1} - \lambda_{r2}^{-1}$ , where  $\lambda_{r2}^{-1}$  is a frequency in the Raman gain spectrum of the active material. As a further example,  $\lambda_{s3}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1} - \lambda_{r2}^{-1} - \lambda_{r3}^{-1}$ , where  $\lambda_{r3}^{-1}$  is a frequency in the Raman gain spectrum of the active material.  $\lambda_{r1}$ ,  $\lambda_{r2}$  and/or  $\lambda_{r3}$  can be the same or different.

**[0011]** The optical fiber can include, for example, three, four, five, six, seven, eight, nine, 10 or more than 10 pairs of reflectors.

**[0012]** In some embodiments, at least one pair of reflectors has a first reflector and a second reflector. The first reflector is disposed in the optical fiber closer to a point where energy at the wavelength  $\lambda_p$  enters the optical fiber than the second reflector, and the second reflector is configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors. The first reflector can be configured to reflect substantially all energy impinging thereon at the resonance frequency for the resonance cavity formed by the at

least one pair of reflectors. The second reflector can be configured to reflect less than about 98% (e.g., less than about 95%, less than about 90%, less than about 75%, less than about 60%, less than about 50%, less than about 25%, less than about 10%) of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors. The amount of energy at the resonance frequency for the resonance cavity that the second reflector is capable of reflecting can be variable.

**[0013]** In certain embodiments, each pair of reflectors has a first reflector and a second reflector, and for each pair of reflectors: the first reflector is disposed in the optical fiber closer to a point where energy at the wavelength  $\lambda_p$  enters the optical fiber than the second reflector and the second reflector is configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

**[0014]** At least one resonance cavity in the optical fiber can have a suppressor disposed therein. The suppressor can be configured to substantially suppress formation of energy at a frequency  $(c/\lambda_x)$  where  $\lambda_x^{-1} = \lambda_z^{-1} - \lambda_a^{-1}$ , and  $(c/\lambda_z)$  is the resonance frequency of the resonance cavity and  $(c/\lambda_a)$  is a frequency in the Raman gain spectrum of the active material in the gain medium of the fiber. The suppressor can be, for example, formed of one or more long period gratings.

**[0015]** One pair of reflectors can have first and second reflectors, and the first and second reflectors can be configured to reflect substantially all energy impinging thereon at the resonance frequency of the corresponding resonance cavity.

**[0016]** In some embodiments, the at least three pairs of reflectors includes a first pair of reflectors and a second pair of reflectors. The first pair of reflectors has first and second reflectors, and the second pair of reflectors has first and second reflectors. The first and second reflectors of the first pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by first pair of reflectors, and the first and second reflectors of the second

pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors.

[0017] In certain embodiments, the at least three pairs of reflectors includes a first pair of reflectors, a second pair of reflectors and a third pair of reflectors. The first pair of reflectors has first and second reflectors, the second pair of reflectors has first and second reflectors, and the third pair of reflectors has first and second reflectors. The first and second reflectors of the first pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the first pair of reflectors, the first and second reflectors of the second pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors, and the first and second reflectors of the third pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the third pair of reflectors.

[0018] The fiber can further include an additional reflector disposed in the optical fiber. The additional reflector can be configured to at least partially reflect energy impinging thereon (e.g., reflect substantially all energy impinging thereon) at the wavelength  $\lambda_p$ .

[0019] One or more of the pairs of reflectors can be formed of a pair of fiber Bragg gratings.

[0020] The Raman active material(s) can be, for example,  $\text{GeO}_2$ ,  $\text{P}_2\text{O}_5$ ,  $\text{SiO}_2$ ,  $\text{B}_2\text{O}_3$  or  $\text{SiO}_x\text{F}_y$ .

[0021] In another aspect, the fiber can be used in a fiber laser system that also includes an energy source configured to emit energy at a wavelength  $\lambda_p$ .

[0022] In a further aspect, the invention features a fiber that includes an optical

fiber containing a gain medium having a Raman active material. The optical fiber is configured to receive energy at a wavelength  $\lambda_p$ . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each pair of reflectors forms a corresponding resonance cavity with a corresponding resonance frequency. The resonance frequency of each resonance cavity is different than the resonance frequency of any other cavity. The optical fiber is substantially devoid of a portion containing more than two of the resonance cavities. The fiber can be incorporated in a system containing an energy source capable of emitting energy at the wavelength  $\lambda_p$ .

**[0023]** In one aspect, the invention features a fiber that includes an optical fiber containing a plurality of sections including a first section having a gain medium including a first Raman active material and a second section having a gain medium including a second Raman active material. The second Raman active material can be the same as or different than the first Raman active material. Alternatively, the concentration of the Raman active material in the second section can be the same as or different than the concentration of the Raman active material in the first section of fiber. Or, the diameter of the fiber core of the second section of fiber can be the same as or different than the diameter of the fiber core of the first section of fiber. The optical fiber is configured to receive energy at a wavelength  $\lambda_p$ . At least three pairs of reflectors are disposed in the optical fiber. Each pair of reflectors forms a corresponding resonance cavity with a corresponding resonance frequency. The optical fiber is substantially devoid of a portion containing more than two of the resonance cavities. The fiber can be incorporated in a system that includes an energy source configured to emit energy at a wavelength  $\lambda_p$ .

**[0024]** In another aspect, the invention features a fiber that includes an optical fiber having a gain medium having a Raman active material. The optical fiber is configured to receive energy at a wavelength  $\lambda_p$ . The fiber also includes a plurality of reflectors disposed in the optical fiber. At least some of the plurality of reflectors form resonance cavities in the optical fiber. Each resonance cavity has a resonance frequency. The resonance frequency of each resonance cavity can be different than the resonance frequency of any other cavity. The plurality of reflectors are configured so that when the

optical fiber receives energy at the wavelength  $\lambda_p$ , the ratio of the output power at a desired wavelength to the pump power can be at least 20% (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

**[0025]** In a further aspect, the invention features a fiber that includes an optical fiber having a gain medium having a Raman active material. The optical fiber is configured to receive energy at a wavelength  $\lambda_p$ . The fiber also includes a plurality of reflectors disposed in the optical fiber. At least some of the plurality of reflectors form resonance cavities in the optical fiber. Each resonance cavity has a resonance frequency. The resonance frequency of each resonance cavity can be different than the resonance frequency of any other cavity. The plurality of reflectors are configured so that when the optical fiber receives energy at the wavelength  $\lambda_p$ , the ratio of the total output power at one or more desired wavelengths to the pump power can be at least 20% (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

**[0026]** In one aspect, the invention features a system that includes a fiber having the structure described herein. The system also includes a splitter configured so that output energy from the fiber can be coupled into the splitter. The system further includes a plurality of optical fibers (e.g., at least five fibers, at least 25 fibers, at least 50 fibers, at least 75 fibers, at least 100 fibers, at least 250 fibers, at least 500 fibers) configured so that energy output from the splitter can be coupled into one or more of the plurality of fibers.

**[0027]** In another aspect, the invention features a system that includes a pump laser and a fiber laser coupled to the pump laser so that energy output by the pump laser can be coupled into the fiber laser. The system also includes a fiber as described herein. The fiber is coupled to the fiber laser so that energy output by the fiber laser can be coupled into the fiber. The system can further include an output cascade coupled to the fiber so that energy output by the fiber can be coupled into the output cascade.



**[0028]** In one aspect, the invention features a fiber that includes an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum. The optical fiber is configured to receive energy at a wavelength  $\lambda_p$ . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each pair of reflectors forms a resonance cavity with a resonance frequency. Each resonance cavity has an index, and the index of each resonance cavity is different than the index of the other resonance cavities. For a resonance cavity having an index with a value M (M is an integer having a value of at least one), the resonance cavity has a resonance frequency  $(c/\lambda_{sm})$ , where  $\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$ , where  $(c/\lambda_{rm})$  is a frequency within the Raman gain spectrum of the Raman active material contained in the gain medium, and c is the speed of light. For a resonance cavity having an index with a value N, the resonance cavity has a resonance frequency  $(c/\lambda_{sn})$ , and the reflectors are configured so that at least two resonance cavities do not overlap. In another aspect, the invention features a system including an energy source coupled to such a fiber.

**[0029]** In some embodiments, the invention can provide a Raman fiber laser having a relatively high output power at one or more desired wavelengths relative to the power of the pump laser that is received by the fiber (e.g., at the wavelength  $\lambda_p$ ). For example, the ratio of the output power at one or more desired wavelengths to the pump power can be at least 20% (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

**[0030]** As used herein, the theoretical limit of the ratio of the output power at a desired wavelength  $\lambda_x$  to the pump power ( $\lambda_p$ ) is the ratio of the wavelength of  $\lambda_p$  to the wavelength of  $\lambda_x$ , when optical losses are neglected.

**[0031]** As used herein, the theoretical limit of the ratio of the total output power at one or more desired wavelengths (e.g.,  $\lambda_x$ ,  $\lambda_y$ ,  $\lambda_z$ ) to the pump power  $\lambda_p$  is the sum of the individual ratios the wavelength of  $\lambda_p$  to the desired wavelength(s) (e.g.,  $\lambda_p/\lambda_x$ ,  $\lambda_p/\lambda_y$ ,

$\lambda_p/\lambda_z$ , respectively).

**[0032]** In some embodiments, the input power can be at least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

**[0033]** In certain embodiments, the output power at a desired wavelength can be at least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

**[0034]** In certain embodiments, the total output power at one or more desired wavelengths can be at least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

**[0035]** In some embodiments, the output power at one or more undesired wavelengths can be relatively low (e.g., less than about one Watt, less than about 0.5 Watt, less than about 0.1 Watt, less than about 0.05 Watt).

**[0036]** In certain embodiments, it is a feature of the invention that  $\lambda_p$  pumps only  $\lambda_{st}$ .

**[0037]** In some embodiments, it is a feature of the invention that energy at a given Stokes shift frequency is pumped only by one other Stokes shift frequency.

**[0038]** In certain embodiments, the fibers can be used as amplifiers rather than lasers.

**[0039]** Features, objects and advantages of the invention are in the description, drawings and claims.

### **Description of Drawings**

**[0040]** Fig. 1 is a schematic representation of an embodiment of a Raman fiber laser system;

**[0041]** Fig. 2 is a plot of output energy intensity as a function of pump energy intensity for embodiments of a Raman fiber laser;

**[0042]** Fig. 3 is a schematic representation of an embodiment of a Raman fiber laser system;

**[0043]** Fig. 4 is a schematic representation of an embodiment of a Raman fiber laser system;

**[0044]** Fig. 5 is a schematic representation of an embodiment of a Raman fiber laser system;

**[0045]** Fig. 6 is a schematic representation of an embodiment of a Raman fiber laser system;

**[0046]** Fig. 7 is a schematic representation of an embodiment of a Raman fiber laser system;

**[0047]** Fig. 8 is a schematic representation of an embodiment of a fiber amplifier system;

**[0048]** Fig. 9 is a schematic representation of an embodiment of a fiber amplifier system;

**[0049]** Fig. 10 is a schematic representation of an embodiment of a fiber laser system;

[0050] Fig. 11 is a schematic representation of an embodiment of a fiber amplifier system; and

[0051] Fig. 12 is a schematic representation of an embodiment of a Raman fiber laser system.

[0052] Like reference symbols in the various drawings indicate like elements.

### **Detailed Description**

[0053] Fig. 1 shows an embodiment of a Raman fiber laser system **1000** including a laser **100** and an optical fiber **110**. Laser **100** is configured so that energy emitted by laser **100** at a wavelength  $\lambda_p$  is coupled into optical fiber **110**. Optical fiber **110** has a gain medium containing a Raman active material. Examples of Raman active materials include  $\text{GeO}_2$ ,  $\text{P}_2\text{O}_5$ ,  $\text{SiO}_2$ ,  $\text{B}_2\text{O}_3$ ,  $\text{SiO}_x\text{F}_y$ , and the like.

[0054] Optical fiber **110** includes a first pair of reflectors **120** and **130** (e.g., a pair of fiber Bragg gratings). Reflector **120** is configured to reflect substantially all (e.g., about 100 %) energy impinging thereon at a wavelength  $\lambda_{s1}$ , where  $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$ , where  $(c/\lambda_{r1})$  is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber **110**, and  $c$  is the speed of light. Reflector **130** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength  $\lambda_{s1}$ . Reflectors **120** and **130** form a resonance cavity **140** in fiber **110** for energy at wavelength  $\lambda_{s1}$ .

[0055] Optical fiber **110** also includes a reflector **125** that is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength  $\lambda_p$ .

[0056] Optical fiber **110** further includes a second pair of reflectors **150** and **160** (e.g., a pair of fiber Bragg gratings). Reflector **150** is configured to reflect substantially

all (e.g., about 100%) energy impinging thereon at a wavelength  $\lambda_{s2}$ , where  $\lambda_{s2}^{-1} = \lambda_{s1}^{-1} - \lambda_{r2}^{-1}$ , where  $(c/\lambda_{r2})$  is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber **110** ( $\lambda_{r2}^{-1}$  may be the same as or different from  $\lambda_{r1}^{-1}$ ). Reflector **160** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength  $\lambda_{s2}$ . Reflectors **150** and **160** form a resonance cavity **170** in fiber **110** for energy at wavelength  $\lambda_{s2}$ . In certain embodiments, reflector **125** is relatively close to reflector **150**. In some embodiments, reflector **150** can be in cavity **170**.

**[0057]** With this arrangement, as energy at  $\lambda_p$  enters optical fiber **110**, the energy at  $\lambda_p$  propagates through fiber **110** and impinges upon reflector **125** where it is reflected and propagates in fiber **110** in the reverse direction. As energy at  $\lambda_p$  propagates through fiber **110**, it interacts with the Raman active material in the gain medium of fiber **110** to create energy at wavelength  $\lambda_{s1}$ . Energy at  $\lambda_{s1}$  in cavity **140** that is propagating in the forward direction impinges upon reflector **130**. A portion of the energy at  $\lambda_{s1}$  that impinges on reflector **130** is reflected backward, and a portion of the energy at  $\lambda_{s1}$  that impinges on reflector **130** continues to propagate through fiber **110** in the forward direction and exits fiber **110** (e.g., at an end **115** of fiber **110**). The portion of energy at  $\lambda_{s1}$  that is reflected by reflector **130** propagates through fiber **110** in the reverse direction until it reaches reflector **120** where it is reflected and then propagates through fiber **110** in the forward direction. Some of the energy at wavelength  $\lambda_{s1}$  continues to propagate in fiber **110** in the forward and in reverse directions in resonance cavity **140**, and some of the energy at wavelength  $\lambda_{s1}$  exits resonance cavity **140** through reflector **130** and ultimately exits fiber **110** (e.g., at end **115**).

**[0058]** As energy at wavelength  $\lambda_{s1}$  propagates through fiber **110**, it interacts with the Raman active material in the gain medium of fiber **110** to create energy at wavelength  $\lambda_{s2}$ . Energy at wavelength  $\lambda_{s2}$  in cavity **170** that is propagating in the reverse direction is

reflected by reflector **150** and then propagates through fiber **110** in the forward direction. Energy at wavelength  $\lambda_{s2}$  propagating in cavity **170** in the forward direction impinges on reflector **160**. Some of the energy at  $\lambda_{s2}$  impinging on reflector **160** is reflected by reflector **160** and then propagates through cavity **170** in the reverse direction, and some of the energy at  $\lambda_{s2}$  impinging on reflector **160** passes through reflector **160** and exits fiber **110** (e.g., at end **115**). It is to be noted that, in this embodiment,  $\lambda_p$  does not directly pump  $\lambda_{s2}$ .

[0059] Resonance cavities **110** and **140** are linked resonance cavities because, while a portion of these cavities overlaps, a portion of the cavities does not overlap.

[0060] Without wishing to be bound by theory, it is believed that this design can allow for enhanced control of the intensity of energy output by fiber **110** at wavelengths  $\lambda_{s1}$  and  $\lambda_{s2}$  by controlling (e.g., independently controlling) the transmission of reflectors **130** and/or **160**, and/or the intensity of the pump energy. For the case where reflector **130** is positioned close to reflector **160** (i.e.,  $z_{125} \approx z_{150}$  and  $z_{130} \approx z_{160}$ , where  $z_x$  is to the position of reflector  $x$ ), it is believed that the performance of fiber **110** can be explained, at least in part, using the following system of equations.

$$\left. \begin{aligned} \frac{dI_p^+}{dz} &= -g_p(I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) \times I_p^+ - \alpha_p I_p^+ = -\frac{dI_p^-}{dz} \\ \frac{dI_{\lambda_{s1}}^+}{dz} &= g_1 I_{\lambda_{s1}}^+ \times (I_p^+ + I_p^-) - \alpha_1 I_{\lambda_{s1}}^+ = -\frac{dI_{\lambda_{s1}}^-}{dz} \end{aligned} \right\} \text{..... along cavity 140}$$

$$\left. \begin{aligned} \frac{dI_{\lambda_{s1}}^+}{dz} &= -\tilde{g}_1 I_{\lambda_{s1}}^+ \times (I_{\lambda_{s2}}^+ + I_{\lambda_{s2}}^-) - \alpha_1 I_{\lambda_{s1}}^+ = -\frac{dI_{\lambda_{s1}}^-}{dz} \\ \frac{dI_{\lambda_{s2}}^+}{dz} &= g_2 I_{\lambda_{s2}}^+ \times (I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) - \alpha_2 I_{\lambda_{s2}}^+ = -\frac{dI_{\lambda_{s2}}^-}{dz} \end{aligned} \right\} \text{..... along cavity 170}$$

with the boundary conditions:

$$\begin{aligned}
I_p^+(z=0) &= I_0; \\
I_p^-(z=z_{125}) &= R_p \times I_p^+(z=z_{125}); \\
I_{\lambda_{s1}}^+(z=z_{120}) &= R_{\lambda_{s1}}^{120} \times I_{\lambda_{s1}}^-(z=z_{120}), I_{\lambda_{s1}}^-(z=z_{130}) = R_{\lambda_{s1}}^{130} \times I_{\lambda_{s1}}^+(z=z_{130}); \\
I_{\lambda_{s2}}^+(z=z_{150}) &= R_{\lambda_{s2}}^{150} \times I_{\lambda_{s2}}^-(z=z_{150}), I_{\lambda_{s2}}^-(z=z_{160}) = R_{\lambda_{s2}}^{160} \times I_{\lambda_{s2}}^+(z=z_{160});
\end{aligned}$$

**[0061]** The indices  $^+$  and  $^-$  represent propagation in fiber **110** from left to right and from right to left, respectively.  $I_p$ ,  $I_{\lambda_{s1}}$ , and  $I_{\lambda_{s2}}$  represent the intensities of energy propagating in fiber **110** at wavelengths  $\lambda_p$ ,  $\lambda_{s1}$  and  $\lambda_{s2}$ , respectively.  $\alpha_p$ ,  $\alpha_1$  and  $\alpha_2$  are the loss coefficients of energy propagating in fiber **110** at wavelengths  $\lambda_p$ ,  $\lambda_{s1}$  and  $\lambda_{s2}$ , respectively, due to, for example, imperfections, scattering and/or splicing in fiber **110**.  $g_p$ ,  $g_1$ ,  $\tilde{g}_1$  and  $g_2$  are the Raman gain coefficients, respectively, of energy propagating in fiber **110** at wavelengths  $\lambda_p$ ,  $\lambda_{s1}$  and  $\lambda_{s2}$ , respectively, due to stimulated Raman scattering (SRS). It is to be noted that  $g_1$  and  $\tilde{g}_1$  represent gain coefficients for energy at  $\lambda_{s1}$  which can correspond to the same or different portion(s) of the Raman gain spectrum of the Raman active material in the gain medium of fiber **110**.  $g_1$  corresponds to SRS energy transfer from  $\lambda_p$  to  $\lambda_{s1}$  and  $\tilde{g}_1$  corresponds to SRS energy transfer from  $\lambda_{s1}$  to  $\lambda_{s2}$ , with respect to  $\lambda_{s1}$ .  $g_2$  is the Raman gain coefficient for the transfer of energy from  $\lambda_{s1}$  to  $\lambda_{s2}$ , with respect to  $\lambda_{s2}$ , and is defined by  $g_2 = (\lambda_{s2}/\lambda_{s1})(\tilde{g}_1)$ . Additionally, in the boundary conditions,  $R_{\lambda_{sy}}^x$  is the reflectance of reflector x at wavelength  $\lambda_{sy}$ , where reflectance is the ratio between reflected and incident intensity.

**[0062]** Based on these equations, it is believed that after reaching generation threshold the intensity of energy output by fiber **110** at wavelength  $\lambda_{s1}$  increases monotonically as the intensity of energy at wavelength  $\lambda_p$  input into fiber **110** is increased until the intensity of energy at  $\lambda_p$  reaches a value  $I_{crit}$ . Below  $I_{crit}$ , the intensity of energy output by fiber **110** at wavelength  $\lambda_{s2}$  is about zero. Above  $I_{crit}$ , the intensity of energy output by fiber **110** at wavelength  $\lambda_{s2}$  increases monotonically while the energy output by fiber **110** at wavelength  $\lambda_{s1}$  remains substantially constant. The particular value of  $I_{crit}$

depends, at least in part, upon the transmission of reflectors **130** and **160**.

[0063] Fig. 2 shows the calculated output intensities for fiber **110** for system **1000** as a function of the intensity of the pump energy ( $\lambda_p$ ) where the reflectance of reflector **130** for energy impinging thereon at wavelength  $\lambda_{s1}$  is varied (20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%) and where reflector **160** reflects 50% of energy impinging thereon at wavelength  $\lambda_{s2}$ . In this example,  $\lambda_{s2}$  is 1480nm,  $\lambda_{s1}$  is 1455nm, and fiber **110** is formed of fused silica with GeO<sub>2</sub> as the Raman active material.

[0064] Fig. 3 shows a Raman fiber laser system **2000** in which fiber **110** includes reflector **125** and pairs of reflectors **120** and **130**, and **150** and **160**. Fiber **110** also includes a pair of reflectors **200** and **210**. Reflector **200** is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at a wavelength  $\lambda_{s3}$ , where  $\lambda_{s3}^{-1} = \lambda_{s2}^{-1} - \lambda_{r3}^{-1}$ , where  $(c/\lambda_{r3})$  is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber **110** ( $\lambda_{r3}^{-1}$  may be the same as or different from  $\lambda_{r2}^{-1}$  and/or  $\lambda_{r1}^{-1}$ ). Reflector **210** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength  $\lambda_{s3}$ . Reflectors **200** and **210** form a resonance cavity **220** in fiber **110** for energy at wavelength  $\lambda_{s3}$ .

[0065] With this arrangement, energy at wavelength  $\lambda_p$  generally propagates in fiber **110** as described above. In addition, energy at wavelengths  $\lambda_{s1}$  and  $\lambda_{s2}$  generally is formed and propagates in fiber **110** as described above. As energy at wavelength  $\lambda_{s2}$  propagates through fiber **110** (e.g., in the overlapping region of cavities **170** and **220**), it interacts with the Raman active material in the gain medium of fiber **110** to create energy at wavelength  $\lambda_{s3}$ . Energy at wavelength  $\lambda_{s3}$  in cavity **220** that is propagating in the reverse direction is reflected by reflector **200** and then propagates through fiber **110** in the forward direction. Energy at wavelength  $\lambda_{s3}$  propagating in cavity **220** in the forward



direction impinges on reflector **210**. Some of the energy at  $\lambda_{s3}$  impinging on reflector **210** is reflected by reflector **210** and then propagates through cavity **220** in the reverse direction, and some of the energy at  $\lambda_{s3}$  impinging on reflector **210** passes through reflector **210** and exits fiber **110** (e.g., at end **115**). It is to be noted that, in this embodiment,  $\lambda_p$  directly pumps only  $\lambda_{s1}$ ,  $\lambda_{s2}$  is directly pumped by only  $\lambda_{s1}$ , and that  $\lambda_{s3}$  is directly pumped only by  $\lambda_{s2}$ .

[0066] Resonance cavities **140** and **170** are linked resonance cavities, and resonance cavities **170** and **220** are linked resonance cavities.

[0067] Fig. 4 shows a Raman fiber laser system **3000** in which fiber **110** includes reflector **125** and pairs of reflectors **120** and **130**, **150** and **160**, and **200** and **210**. Fiber **110** also includes a pair of reflectors **300** and **310**. Reflector **300** is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at a wavelength  $\lambda_{s4}$ , where  $\lambda_{s4}^{-1} = \lambda_{s3}^{-1} - \lambda_{r4}^{-1}$ , where  $(c/\lambda_{r4})$  is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber **110** ( $\lambda_{r4}^{-1}$  may be the same as or different from  $\lambda_{r3}^{-1}$ ,  $\lambda_{r2}^{-1}$  and/or  $\lambda_{r1}^{-1}$ ). Reflector **310** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength  $\lambda_{s4}$ . Reflectors **300** and **310** form a resonance cavity **320** in fiber **110** for energy at wavelength  $\lambda_{s4}$ .

[0068] With this arrangement, energy at wavelength  $\lambda_p$  generally propagates in fiber **110** as described above. In addition, energy at wavelengths  $\lambda_{s1}$ ,  $\lambda_{s2}$  and  $\lambda_{s3}$  generally is formed and propagates in fiber **110** as described above. As energy at wavelength  $\lambda_{s3}$  propagates through fiber **110** (e.g., in the overlapping region of cavities **220** and **320**), it interacts with the Raman active material in the gain medium of fiber **110** to create energy at wavelength  $\lambda_{s4}$ . Energy at wavelength  $\lambda_{s4}$  in cavity **320** that is propagating in the reverse direction is reflected by reflector **300** and then propagates

through fiber 110 in the forward direction. Energy at wavelength  $\lambda_{s4}$  propagating in cavity 320 in the forward direction impinges on reflector 310. Some of the energy at  $\lambda_{s4}$  impinging on reflector 310 is reflected by reflector 310 and then propagates through cavity 320 in the reverse direction, and some of the energy at  $\lambda_{s4}$  impinging on reflector 310 passes through reflector 310 and exits fiber 110 (e.g., at end 115). It is to be noted that, in this embodiment,  $\lambda_p$  directly pumps only  $\lambda_{s1}$ ,  $\lambda_{s2}$  is directly pumped by only  $\lambda_{s1}$ ,  $\lambda_{s3}$  is directly pumped only by  $\lambda_{s2}$ , and  $\lambda_{s4}$  is directly pumped only by  $\lambda_{s3}$ .

[0069] Resonance cavities 140 and 170 are linked cavities, resonance cavities 170 and 220 are linked cavities, and resonance cavities 170 and 220 are linked cavities.

[0070] While the foregoing description has been made for a system containing two, three or four pairs of reflectors, the invention is not limited in this manner. Rather, the number of pairs of reflectors can be greater than two (e.g., five pairs of reflectors, six pairs of reflectors, seven pairs of reflectors, eight pairs of reflectors, nine pairs of reflectors, 10 pairs of reflectors, etc.). In general, the pairs of reflectors are arranged so that each pair of reflectors forms a resonance cavity at a respective wavelength corresponding to a Raman Stokes shift. Typically, each pair of reflectors includes one reflector that reflects substantially all (e.g., about 100%) energy at the Raman Stokes shift wavelength (e.g., disposed closer to the point of the optical fiber where the pump energy enters the fiber) and one reflector that partially reflects energy at the Raman Stokes shift wavelength (e.g., disposed further from the point of the optical fiber where the pump energy enters the fiber). Usually, the resonance cavities are arranged so that the resonance cavity for energy at the wavelength  $\lambda_{sn}$  overlaps only with a maximum of two resonance cavities. One of the two resonance cavities is for energy at the wavelength  $\lambda_{sn-1}$ , where  $\lambda_{sn-1}^{-1} = \lambda_{sn}^{-1} + \lambda_m^{-1}$  and the other of the two resonance cavities is for energy at the wavelength  $\lambda_{sn+1}$ , where  $\lambda_{sn+1}^{-1} = \lambda_{sn}^{-1} + \lambda_{m+1}^{-1}$  ( $\lambda_m^{-1}$  and  $\lambda_{m+1}^{-1}$  being Stokes shifts within the Raman gain spectrum of the active material in the gain medium of fiber 110;  $\lambda_m^{-1}$  and  $\lambda_{m+1}^{-1}$  being the same or different). Generally, relative to the resonance cavity for energy at wavelength  $\lambda_{sn}$ , the resonance cavity for energy at  $\lambda_{sn-1}$  is closer to the

portion of fiber 110 where the energy at wavelength  $\lambda_p$  enters fiber 110, and the resonance cavity for energy at  $\lambda_{sn+1}$  is further from the portion of fiber 110 where the energy at wavelength  $\lambda_p$  enters fiber 110. Typically, the resonance cavity having a resonance frequency closest to  $\lambda_p^{-1}$  overlaps with only one other resonance cavity, and the resonance cavity having a resonance frequency furthest from  $\lambda_p^{-1}$  overlaps with only one other resonance cavity.

[0071] Although systems have been described in which each resonance cavity is formed of a pair of reflectors with one reflector that only partially reflects energy at the corresponding wavelength of the resonance cavity, the invention is not limited in this sense. In certain embodiments, one or more of the pairs of reflectors can have both reflectors that only partially reflect energy at the corresponding wavelength of the resonance cavity. In some embodiments, one or more of the pairs of reflectors can have both reflectors that reflect substantially (e.g., about 100%) the energy at the corresponding wavelength of the resonance cavity.

[0072] Moreover, the invention is not limited to systems in which the reflectance of a reflector is fixed. In some embodiments, the reflectance of a reflector can be variable. For example, the amount of energy reflected off reflectors 130, 160, 210, and/or 310 at their respective corresponding wavelengths can be variable. In certain embodiments, the amount of energy reflected off reflectors 120, 150, 200, and/or 300 at their respective corresponding wavelengths can be variable. Various combinations of tunable reflectors are contemplated. Furthermore, these systems can include, for example, appropriate electronics to form a feedback loop so that the systems can monitor the intensity of energy output at one or more wavelengths and vary the reflectance of one or more reflectors (e.g., vary the reflectance of one or more reflectors in real time) to obtain one or more desired output intensities at one or more wavelengths.

[0073] In certain embodiments, a reflector can be formed of a variable output coupler. Such couplers are described, for example, in commonly owned P.C.T. Patent Application Serial PCT/US02/19420, filed on June 19, 2002, and entitled "Apparatus and

Method for Variable Optical Output Control”, and published as WO 03/001262 A1 on January 3, 2003, and which is hereby incorporated by reference.

**[0074]** In addition, one or more of the resonance cavities contained within a Raman fiber laser system can contain a suppressor that is designed to substantially reduce (e.g., substantially eliminate) the formation of unwanted energy in the resonance cavity or cavities. Typically, such unwanted energy corresponds to energy at higher order Stokes shifts than the resonance energy for the resonance cavity. The suppressor can be, for example, a long period grating having a resonance frequency corresponding to the frequency of the undesired energy.

**[0075]** In some embodiments, an optical fiber can be formed of more than one segment of fiber coupled together. For example, Fig. 5 shows a Raman fiber laser system **7000** including laser **100** and an optical fiber **705**. Optical fiber **705** has a first section **720** with a gain medium containing a Raman active material and a second section **730** with a gain medium containing a Raman active material. Sections **720** and **730** are coupled together at point **710** (e.g., spliced together). The Raman active material of the gain medium in section **720** may be the same as or different from the Raman active material of the gain medium in section **730**. In some embodiments, sections **720** and **730** may have the same Raman active material in their respective gain media, but the concentration of the Raman active material in section **720** is different than the concentration of the Raman active material in section **730**. In certain embodiments, sections **720** and **730** may have the same Raman active material in their respective gain media, but the radius of the portion of section **720** that contains the Raman active material is different than the radius of the portion of section **730** that contains the Raman active material in section **730**. Various combinations of active material, radius and active material concentration in segments **720** and **730**, respectively, can be used. It is to be noted that in embodiments where sections **720** and **730** contain the same Raman active material having the same concentration and radius, the position of splice point **710** can have substantially no impact on the performance of system **7000**.

**[0076]** Optical fiber **705** includes reflector **125**, and pairs of reflectors **725** and **735** forming resonance cavity **740**. Reflector **725** is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength  $\lambda_{s1}$ , where  $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$  and  $(c/\lambda_{r1})$  is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section **720**. Reflector **735** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength  $\lambda_{s1}$ . Reflectors **725** and **735** form a resonance cavity **740** in fiber **705** for energy at wavelength  $\lambda_{s1}$ . A portion of resonance cavity **740** is in section **720** of fiber **705**, and a portion of resonance cavity **740** is in section **730** of fiber **705**.

**[0077]** Fiber **705** further includes a pair of reflectors **750** and **760**. Reflector **750** is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength  $\lambda_{s1}'$ , where  $\lambda_{s1}'^{-1} = \lambda_{s1}^{-1} - \lambda_{r1}'^{-1}$  and  $(c/\lambda_{r1}')$  is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section **730**. Reflector **760** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength  $\lambda_{s1}'$ . Reflectors **750** and **760** form a resonance cavity **770** in fiber **705** for energy at wavelength  $\lambda_{s1}'$ .

**[0078]** With this arrangement, energy at wavelength  $\lambda_p$  enters optical fiber **705** in section **720**. The energy at  $\lambda_p$  propagates through section **720** of fiber **705** and impinges upon reflector **125** where it is reflected and propagates in section **720** of fiber **705** in the reverse direction. As energy at  $\lambda_p$  propagates through section **720** of fiber **705** it interacts with the Raman active material in the gain medium of section **720** of fiber **705** to create energy at wavelength  $\lambda_{s1}$ . Energy at  $\lambda_{s1}$  in cavity **740** that is propagating in the forward direction can propagate in the gain medium of sections **720** and **730** prior to impinging upon reflector **735**. A portion of the energy at  $\lambda_{s1}$  that impinges on reflector **735**

continues to propagate through fiber **705** in the forward direction and exits fiber **705** (e.g., at an end **715** of fiber **705**). The portion of energy at  $\lambda_{s1}$  that is reflected by reflector **735** can propagate in sections **720** and **730** of fiber **705** in the reverse direction until it reaches reflector **725** where it is reflected and propagates through fiber **705** in the forward direction within cavity **740**.

[0079] As energy at  $\lambda_{s1}$  propagates in section **730** of fiber **705** (e.g., between splice point **710** and reflector **735**), it can interact with the Raman active material of the gain medium of section **730** to create energy at wavelength  $\lambda_{s1'}$ . Energy at wavelength  $\lambda_{s1'}$  in cavity **770** that is propagating in the reverse direction is reflected by reflector **750** and then propagates through fiber **705** in the forward direction. Energy at wavelength  $\lambda_{s1'}$  propagating in cavity **770** in the forward direction impinges on reflector **760**. Some of the energy impinging on reflector **760** is reflected by reflector **760** and then propagates through cavity **770** in the reverse direction, and some energy at  $\lambda_{s1'}$  impinging on reflector **760** passes through reflector **760** and exits fiber **705** (e.g., at end **715**). It is to be noted that, in this embodiment,  $\lambda_p$  directly pumps only  $\lambda_{s1}$ , and that  $\lambda_{s1'}$  is directly pumped only by  $\lambda_{s1}$ . The order of the reflectors, however, can be varied. For example, reflector **760** can be located to the left of reflector **735**, or the right side of splice point **710**, or the like.

[0080] Resonance cavities **740** and **770** are linked cavities.

[0081] Without wishing to be bound by theory, it is believed that this design can allow for enhanced control of the intensity of energy output by fiber **705** at wavelengths  $\lambda_{s1}$  and  $\lambda_{s1'}$  by controlling (e.g., independently controlling) the transmission of reflectors **735** and/or **760**, and/or the intensity of the pump energy. It is believed that the performance of fiber **705**, in the case where reflector **735** is positioned in close proximity to reflector **760** (i.e.,  $z_{125} \approx z_{750} \approx z_{710}$  and  $z_{735} \approx z_{760}$ ), can be explained, at least in part, using the following system of equations.

$$\begin{aligned}
\frac{dI_p^+}{dz} &= -g_p (I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) \times I_p^+ - \alpha_p I_p^+ = -\frac{dI_p^-}{dz} \\
\frac{d\hat{I}_{\lambda_{s1}}^+}{dz} &= g_1 \hat{I}_{\lambda_{s1}}^+ \times (I_p^+ + I_p^-) - \alpha_1 \hat{I}_{\lambda_{s1}}^+ = -\frac{d\hat{I}_{\lambda_{s1}}^-}{dz} \\
\frac{d\tilde{I}_{\lambda_{s1}}^+}{dz} &= -\tilde{g}_1 \tilde{I}_{\lambda_{s1}}^+ \times (I_{\lambda_{s1}'}^+ + I_{\lambda_{s1}'}^-) - \tilde{\alpha}_1 I_{\lambda_{s1}}^+ = -\frac{d\tilde{I}_{\lambda_{s1}}^-}{dz} \\
\frac{dI_{\lambda_{s1}'}^+}{dz} &= g_1' I_{\lambda_{s1}'}^+ \times (\tilde{I}_{\lambda_{s1}}^+ + \tilde{I}_{\lambda_{s1}}^-) - \alpha_1' I_{\lambda_{s1}'}^+ = -\frac{dI_{\lambda_{s1}'}^-}{dz}
\end{aligned}$$

[0082] The indices  $^+$  and  $^-$  represent propagation in fiber 705 from left to right and from right to left, respectively.  $I_p$ ,  $I_{\lambda_{s1}}$ , and  $I_{\lambda_{s1}'}$  represent the intensities of energy propagating in fiber 705 at wavelengths  $\lambda_p$ ,  $\lambda_{s1}$  and  $\lambda_{s1}'$ , respectively.  $\alpha_p$ ,  $\alpha_1$ , are the loss coefficients of energy propagating in fiber 705 at wavelengths  $\lambda_p$  and  $\lambda_{s1}$ , respectively, due to, for example, imperfections, scattering and/or splicing in fiber 705.  $\alpha_1$  and  $\tilde{\alpha}_1$  are loss coefficients for sections 720 and 730, respectively, for energy at wavelength  $\lambda_{s1}$  (e.g., due to imperfections, scattering and/or splicing).  $g_p$  and  $g_1$  are the Raman gain coefficients for energy propagating in fiber 705 at wavelengths  $\lambda_p$  and  $\lambda_{s1}$ , respectively, due to power gain from stimulated Raman scattering (SRS).  $g_1, \tilde{g}_1$  are Raman gain coefficients for energy propagating in sections 720 and 730, respectively, at  $\lambda_{s1}$  due to power gain from stimulated Raman scattering (SRS).  $g_1' = (\lambda_{s1}'/\lambda_{s1})(\tilde{g}_1)$ . The boundary conditions at the reflectors and splice point are given by:

$$\begin{aligned}
I_p^+(z=0) &= I_0; I_p^-(z=z_{125}) = R_{\lambda_p}^{125} \times I_p^+(z=z_{125}); \\
\hat{I}_{\lambda_{s1}}^+(z=z_s) &= \tilde{I}_{\lambda_{s1}}^+(z=z_s); \hat{I}_{\lambda_{s1}}^-(z=z_s) = \tilde{I}_{\lambda_{s1}}^-(z=z_s); \\
\hat{I}_{\lambda_{s1}}^+(z=z_{725}) &= R_{\lambda_{s1}}^{725} \times \hat{I}_{\lambda_{s1}}^-(z=z_{725}); \tilde{I}_{\lambda_{s1}}^-(z=z_{735}) = R_{\lambda_{s1}}^{735} \times \tilde{I}_{\lambda_{s1}}^+(z=z_{735}); \\
I_{\lambda_{s1}'}^+(z=z_{750}) &= R_{\lambda_{s1}'}^{750} \times I_{\lambda_{s1}'}^-(z=z_{750}); I_{\lambda_{s1}'}^-(z=z_{760}) = R_{\lambda_{s1}'}^{760} \times I_{\lambda_{s1}'}^+(z=z_{760});
\end{aligned}$$

Here  $z_s$  is the splice point of two fibers, and  $z_x$  and  $R_{\lambda_{sy}}^x$  are as defined above.  $I_0$  is the total pump power.

[0083] Fig. 6 shows a Raman fiber laser system **8000** including laser **100** and optical fiber **705** with sections **720** and **730** coupled at point **710**. Fiber **705** includes reflector **125**, and pairs of reflectors **725** and **735**, and **750** and **760**, forming resonance cavities **740** and **770**, respectively. Fiber **110** also includes a pair of reflectors **850** and **860** (e.g., fiber Bragg gratings). Reflector **850** is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength  $\lambda_{s2}$ , where  $\lambda_{s2}^{-1} = \lambda_{s1}^{-1} - \lambda_{r2}^{-1}$ , and  $(c/\lambda_{r2})$  is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section **730** ( $\lambda_{r2}^{-1}$  can be the same as or different from  $\lambda_{r1}^{-1}$ ). Reflector **860** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength  $\lambda_{s2}$ . Reflectors **850** and **860** form a resonance cavity **870** in fiber **705** for energy at wavelength  $\lambda_{s2}$ .

[0084] With this arrangement, energy at  $\lambda_p$  generally propagates in fiber **705** as described above. In addition energy at wavelengths  $\lambda_{s1}$  and  $\lambda_{s1}'$  generally is formed and propagates through fiber **705** as described above. As energy at wavelength  $\lambda_{s1}'$  propagates through section **730** of fiber **705** (e.g., in the region overlapping cavities **770** and **870**), it interacts with the Raman active material of section **730** of fiber **705** to create energy at wavelength  $\lambda_{s2}$ . Energy at wavelength  $\lambda_{s2}$  in cavity **870** that is propagating in the reverse direction is reflected by reflector **850** and then it propagates through fiber **705** in the forward direction. Energy at wavelength  $\lambda_{s2}$  propagating in cavity **870** in the forward direction impinges on reflector **860**. Some of the energy at  $\lambda_{s2}$  impinging on reflector **860** is reflected by reflector **860** and then propagates through cavity **870** in the reverse direction, and some of the energy at  $\lambda_{s2}$  impinging on reflector **860** passes through reflector **860** and exits fiber **705** (e.g., at end **715**). It is to be noted that, in this embodiment,  $\lambda_p$  directly pumps only  $\lambda_{s1}$ ,  $\lambda_{s1}'$  is directly pumped only by  $\lambda_{s1}$ , and  $\lambda_{s2}$  is directly pumped only by  $\lambda_{s1}'$ .

[0085] Resonance cavities **740** and **770** are linked cavities, and resonance cavities



770 and 870 are linked cavities.

[0086] Fig. 7 shows a Raman fiber laser system 9000 including laser 100 and optical fiber 705 with sections 720 and 730 coupled at point 710. Fiber 705 includes reflector 125, and pairs of reflectors 725 and 735, 750 and 760, and 850 and 860, forming resonance cavities 740, 770 and 870, respectively. Fiber 705 also includes a pair of reflectors 950 and 960 (e.g., fiber Bragg gratings). Reflector 950 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength  $\lambda_{s3}'$ , where  $\lambda_{s3}'^{-1} = \lambda_{s2}'^{-1} - \lambda_{r3}'^{-1}$ , and  $(c/\lambda_{r3}')$  is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section 730 ( $\lambda_{s3}'^{-1}$  can be the same as or different than  $\lambda_{r1}'^{-1}$  and/or  $\lambda_{r2}'^{-1}$ ). Reflector 960 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength  $\lambda_{s3}'$ . Reflectors 950 and 960 form a resonance cavity 970 in fiber 705 for energy at wavelength  $\lambda_{s3}'$ .

[0087] With this arrangement, energy at  $\lambda_p$  generally propagates in fiber 705 as described above. In addition energy at wavelengths  $\lambda_{s1}$ ,  $\lambda_{s1}'$  and  $\lambda_{s2}'$  generally is formed and propagates through fiber 705 as described above. As energy at wavelength  $\lambda_{s2}'$  propagates through section 730 of fiber 705 (e.g., in the region overlapping cavities 870 and 970), it interacts with the Raman active material of section 730 of fiber 705 to create energy at wavelength  $\lambda_{s3}'$ . Energy at wavelength  $\lambda_{s3}'$  in cavity 970 that is propagating in the reverse direction is reflected by reflector 950 and then it propagates through fiber 705 in the forward direction. Energy at wavelength  $\lambda_{s3}'$  propagating in cavity 970 in the forward direction impinges on reflector 960. Some of the energy at  $\lambda_{s3}'$  impinging on reflector 960 is reflected by reflector 960 and then propagates through cavity 970 in the reverse direction, and some of the energy at  $\lambda_{s3}'$  impinging on reflector 960 passes through reflector 960 and exits fiber 705 (e.g., at end 715). It is to be noted that, in this embodiment,  $\lambda_p$  directly pumps only  $\lambda_{s1}$ ,  $\lambda_{s1}'$  is directly pumped only by  $\lambda_{s1}$ ,  $\lambda_{s2}'$  is

directly pumped only by  $\lambda_{s1}$ , and  $\lambda_{s3}$ , is directly pumped only by  $\lambda_{s2}$ .

[0088] Resonance cavities **740** and **770** are linked cavities, resonance cavities **770** and **870** are linked cavities, and resonance cavities **870** and **970** are linked cavities.

[0089] Although optical fibers with coupled segments having certain arrangements of splice points and reflectors have been described, the invention is not limited to such arrangements. In general, the splice points and reflectors can be arranged as appropriate to achieve one or more desired output intensities at one or more output wavelengths. As an example, with reference to Fig. 7, splice point **710** can optionally be between reflectors **725** and **750** or between reflectors **735** and **760**. As another example, with reference to Fig. 8, splice point **710** can optionally be between reflectors **725** and **750**, between reflectors **735** and **850**, between reflectors **850** and **760** or between reflectors **760** and **860**. In a further example, with reference to Fig. 9, splice point **710** can optionally be between reflectors **725** and **750**, between reflectors **735** and **850**, between reflectors **850** and **760**, between reflectors **760** and **950**, between reflectors **950** and **860** or between reflectors **960** and **860**. Typically, the reflectors are arranged so that the resonance cavity for energy at a particular wavelength  $\lambda_{sn}$  overlaps only with two resonance cavities (see discussion above). Moreover, it is to be understood that the number of resonance cavities, or portions of resonance cavities, in a particular segment of fiber can be varied as desired.

[0090] In addition, while systems containing an optical fiber with two segments of material have been disclosed, optical fibers having different numbers of segments can also be used. In general, the optical fiber can have N segments, where N is an integer greater than or equal to one. For example, the optical fiber can include more than two segments of material having the same or different Raman active material(s) (e.g., three segments, four segments, five segments, six segments, seven segments, eight segments, nine segments, 10 segments, etc.). In general, each section of the optical fiber can have a gain medium with an Raman active material which can be the same or different than the Raman active material in the gain medium of the neighboring section(s) of the fiber. In

some embodiments, all sections of the optical fiber have a gain medium with the same Raman active material. In certain embodiments, all sections of the optical fiber have a gain medium with a different Raman active material than the Raman active material in the gain medium of the other sections. In some embodiments the Raman active material in the gain medium of the other sections can alternate. For example, a three-section optical fiber can be formed in which the Raman active material of the gain medium of the first and third sections is the same, and in which the Raman active material in the gain medium in the middle section is different. Other arrangements are contemplated.

[0091] Furthermore, while Raman fiber lasers and Raman fiber laser systems have been described in which sections of the optical fiber are spliced together, the invention is not limited in this sense. Generally, the sections of the fiber are coupled together so that energy can propagate therebetween. Typically, the sections of fiber are contiguous. For example, in some embodiments, two neighboring sections of the optical fiber can be connected by a lens (e.g., a Green lens). Optionally, free-space optics can be used to couple one or more segments of fiber.

[0092] Fig. 8 is a schematic view of an embodiment of a fiber amplifier system 1100 in which a Raman fiber laser system 1105 that outputs energy at four wavelengths ( $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ ) is used to amplify the signals propagating along fibers 1122, 1124, 1126, and 1128 respectively. These output wavelengths exit system 1105 and enter a fiber 1108. Fiber 1108 is coupled to a splitter 1110, which couples a portion of the output energy at each wavelength ( $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ ) into fibers 1112, 1114, 1116, and 1118. The pump energy at each wavelength in each fiber 1112, 1114, 1116, and 1118 is coupled into fibers 1122, 1124, 1126, and 1128 respectively, via couplers 1132, 1134, 1136, and 1138 respectively. At least a portion of each of fibers 1122, 1124, 1126, and 1128 contain a gain medium that has a Raman active material. In fibers 1122, 1124, 1126, and 1128 the input signals interact with the pump energy from fibers 1112, 1114, 1116, and 1118, respectively and are amplified by stimulated Raman scattering.

[0093] Of course such a system is not limited to amplification of signals in four

fibers, or amplification by four wavelengths. In general, a Raman fiber laser system with N output wavelengths, where N is an integer greater than or equal to one (e.g., one, two, three, four, five, six, seven, eight, nine, 10, etc.) can be used to amplify the signal in M different fibers, where M is an integer greater than or equal to one (e.g., one, two, three, four, five, six, seven, eight, nine, 10, etc.). In certain embodiments, M can be, for example, on the order of one hundred or more. In some embodiments, all the fibers in which the signals are amplified by the Raman fiber laser may be bound together in a single or several cables running in parallel (e.g., an under water fiber optic and/or ultra long haul applications).

[0094] Figure 9 depicts an embodiment of a fiber amplifier system **12000**. System **12000** utilizes four Raman fiber laser systems **1210**, **1220**, **1230**, and **1240**, each system emitting energy at an output wavelength that exits systems **1210**, **1220**, **1230**, and **1240** through fibers **1250**, **1260**, **1270**, and **1280**, respectively. The output energy from each laser **1210**, **1220**, **1230**, and **1240**, is coupled into at least one of the fibers **1112**, **1114**, **1116**, and **1118** via a cross-coupler (e.g., a WDM) **1290**. In some embodiments, a portion of output energy at each wavelength generated by each laser system **1210**, **1220**, **1230**, and **1240** is coupled into each fiber **1112**, **1114**, **1116**, and **1118**, respectively via coupler **1290**. The pump energy at each wavelength in each fiber **1112**, **1114**, **1116**, and **1118** is coupled into fibers **1122**, **1124**, **1126**, and **1128** respectively, via coupler **1132**, **1134**, **1136**, and **1138** respectively. At least a portion of fibers **1122**, **1124**, **1126**, and **1128** contain a gain medium that has a Raman active material. In fibers **1122**, **1124**, **1126**, and **1128** the input signals interact with the pump energy and are amplified by stimulated Raman scattering.

[0095] Such a system **12000** is not limited to four lasers or four fibers. Any number of lasers may amplify the signal in any number of fibers. Moreover, a given fiber laser system can output more than one wavelength, which can be coupled into one or more fibers.

[0096] A further example of a fiber laser system **13000** is depicted schematically

in Figure 10. System **13000** includes a pump laser **1310** (e.g., a semiconductor diode laser) that is connected to a coupler **1350** via fibers **1320**, **1330** and **1340**. Combiner **1350** is connected to a fiber laser **1370** (e.g., a Ytterbium-doped double clad fiber) via a coupler **1360**. Laser **1370** is in turn connected to Raman a fiber laser **1390** (e.g., a Raman fiber laser having the structure described herein) via a coupler **1380**, and a laser **1390** is connected to an output cascade **1510** via fiber a coupler **1400**. In certain embodiments, laser **1390** and output cascade **1510** are integrated in a single unit.

[0097] During operation, energy at wavelength  $\Lambda_p$  is generated by pump laser **1310** and propagates along fibers **1320**, **1330**, and **1340** and is coupled into fiber laser **1370** via combiner **1350** and coupler **1360**. The energy at  $\Lambda_p$  is converted by laser **1370** into energy at  $\lambda_p$ . Energy at  $\lambda_p$  exits laser **1370**, propagates along coupler **1380** and is coupled into Raman fiber laser **1390**. Energy at wavelength  $\lambda_p$  is converted to energy at one or more longer wavelengths. The energy at these wavelengths is coupled into output cascade **1510** by fiber **1400**. Cascade **1510** optionally includes variable output couplers that can be dynamically adjusted to regulate the amount of energy allowed to exit system **13000** at desired wavelengths.

[0098] While certain embodiments have been described, the invention is not limited to these embodiments. For example, one or more sections of an optical fiber can be substantially devoid of a gain medium having a Raman active material. As a further example, the reflectors need not be in the form of fiber Bragg gratings. For example, one or more of the reflectors can be a loop mirror, or one or more reflectors can be in the form of a coated mirror (e.g., a coated mirror at one or both ends of a section of optical fiber). As another example, the suppressor(s) need not be in the form of LPG(s). For example, one or more of the suppressors can be in the form of gratings e.g., short period gratings, slanted gratings, etc.) that are substantially non-perpendicular to the length of the fiber along which energy propagates. In these embodiments, the angle and/or period of the gratings can be selected to scatter one or more wavelengths of interest (e.g., one or more higher order Raman Stokes shift wavelengths). As an additional example, the type of laser used for pumping can be varied. Examples of lasers that can be used include

semiconductor diode lasers (e.g., high power semiconductor diode lasers), double clad doped fiber lasers, conventional free space coupled lasers, and the like. As another example, various types of optical fibers can be used, including, for example, double clad optical fibers and polarization maintaining optical fibers. Furthermore, the optical fibers can be formed of, for example, silica based materials (e.g., fused silica based) or fluoride-based materials. As yet another example, the relative and/or absolute lengths of one or more of the sections of the optical fiber can be varied based upon the intended use of the Raman fiber laser.

[0099] Moreover, while the fibers and systems have been described as Raman fiber lasers and Raman fiber laser systems, those skilled in the art will appreciate that the general concepts described can be extended to provide amplifiers and amplifier systems. Generally, a fiber amplifier provides gain for energy at a wavelength or wavelength range of interest without the use of a resonance cavity (e.g., without a resonator) or with an optical cavity operating below resonance threshold. Fig. 11 is a schematic view of an embodiment of a fiber amplifier system 10000 in which a fiber 1050 is used as a signal amplifier. Fiber 1050 can be formed of multiple segments of fiber or a single segment of fiber. To operate at below resonance threshold, for example, one or more of the reflectors can be removed from fiber 1050 and/or the reflectivity of one or more of the reflectors can be reduced. An input signal enters system 10000 via fiber 1005 (the reflectors can be, for example, otherwise arranged as described above). Energy source 1060 emits a pump signal 1070. The input signal in fiber 1005 and pump signal 1070 are coupled into fiber 1050 via coupler 1080. Such couplers are known to those skilled in the art. Pump signal 1070 interacts with the Raman active material(s) in the sections of fiber 1050, and the input signal is amplified. A device 1090 (e.g., a WDM coupler) separates the amplified input signal from the Stokes shifted pump signal so that the Stokes shifted pump signal travels along fiber 1015, and the amplified input signal travels along fiber 1025. While Fig. 13 shows one embodiment of fiber 1050 in a fiber amplifier system, other fiber amplifier systems in which fiber 1050 can be used will be apparent to those of skill in the art.

**[0100]** Furthermore, while the foregoing discussion has been with respect to linked resonance cavities, the invention is not so limited. In certain embodiments, the systems can be formed of a hybrid of linked and nested resonance cavities. Nested resonance cavities refer to resonance cavities in which one resonance cavity is entirely contained within another resonance cavity. For example, Fig. 12 shows a system **12000** including an optical fiber **110**, a pair of reflectors **12010** and **12020** (which reflect substantially all energy at wavelength  $\lambda_{s1}$ ) a pair of reflectors **12030** and **12040** (which reflect substantially all energy at wavelength  $\lambda_{s2}$ ) a pair of reflectors **12050** and **12060** (which reflect substantially all energy at wavelength  $\lambda_{s3}$ ) a pair of reflectors **12070** and **12080** (which reflect substantially all energy at wavelength  $\lambda_{s4}$ ) and a pair of reflectors **12090** and **12100** (which reflect substantially all energy at wavelength  $\lambda_{s5}$ ) where  $\lambda_{sn}$  is determined as described above. With this configuration, reflectors **12030** and **12040** form a resonance cavity **12110** that is nested within a resonance cavity **12120** formed by reflectors **12010** and **12020**, and reflectors **12070** and **12080** form a resonance cavity **12140** that is nested within a resonance cavity **12130** formed by reflectors **12090** and **12100**. In addition, reflectors **12050** and **12060** form a resonance cavity **12150**. Resonance cavity **12150** is linked with resonance cavity **12110**, and resonance cavity **12150** is linked with resonance cavity **12120**. Resonance cavity **12150** is linked with resonance cavity **12130**, and resonance cavity **12150** is linked with resonance cavity **12140**.

Other embodiments are in the claims.

WHAT IS CLAIMED IS: